

*Secondary  $\beta$ -rays.*

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In various papers\* published during the last three years I have given an account of work dealing with the emission of secondary  $\beta$ -rays by substances when exposed to the  $\beta$ -rays from radium. The present paper deals with some further points of importance connected with the same subject.

It is not necessary to summarise with any detail the results discussed in previous papers, but the following facts may be briefly mentioned. In these papers no steps were taken to separate the effects due to the primary  $\beta$  radium rays from those produced by the  $\gamma$ -rays that accompanied them; it was sufficiently clear from a few preliminary experiments that the secondary effects due to the  $\gamma$ -rays were very small compared with those produced by the  $\beta$ -rays. As this point has been referred to by other workers† when discussing the results, and as much as 20 per cent. of the total secondary taken as possibly consisting of secondary  $\gamma$ -rays or secondary  $\beta$ -rays due to the  $\gamma$ -rays, I have made some further experiments on the subject.

In the first place, the fraction of the total secondary due to the incident  $\gamma$ -rays was determined by using a magnetic field to deflect the incident  $\beta$ -rays. With the strongest field used the total secondary radiation was cut down to about 4 per cent. of its value when the field was off. This experiment was carried out with the secondary radiation from lead and also from aluminium. The composition of the secondary radiation was then tested by using the magnetic field to deflect it, and it was found to consist almost entirely of  $\beta$ -rays. In both these types of experiments the pencil of rays used and the measuring apparatus employed were taken quite similar to what had been used in the previous work, so that the results I have published in previous papers may be taken as applying to secondary rays, more than 99 per cent. of which are  $\beta$ -rays, and of which 96 per cent. are produced by the

\* 'Phil. Mag.' February, 1905.

'Royal Dublin Society's Trans.'—

"Secondary Radiation," March, 1905.

"Secondary Radiation (Part II) and Atomic Structure," May, 1905.

"The Energy of Secondary Radiation," February, 1906.

"Secondary Radiation from Compounds" (with Mr. Hackett), April, 1906.

"The Absorption of  $\beta$  Radium Rays by Matter" (with Mr. Hackett), March, 1907.

† Kleeman, 'Phil. Mag.,' November, 1907.

incident  $\beta$  radium rays. The same holds for the further results discussed in this paper.

As described in the previous papers, the relative intensity of the secondary radiation has been measured under exactly similar conditions for a large number of elements, and found to depend on the atomic weight of the element, the secondary radiation increasing with the atomic weight, and the rate of increase being such as to divide the elements into divisions corresponding to the chemical periods. The continuous curves (curves D, p. 511), on which the elements are marked without suffix, are taken from a previous paper, and show the relation between the intensity of the secondary radiation and the atomic weight. Further work showed that the rarer elements of the third long period fell into the place reserved for them in this series of curves between iodine and tungsten, the secondary radiation increasing very little with atomic weight in the case of these elements, which fact may be compared with their want of well-defined chemical differences.

The secondary radiation from a large number of compounds was measured and compared with that from the constituent elements, and it was thus shown that the secondary emission of  $\beta$ -particles was strictly an additive atomic property. This result rendered it possible to deduce the secondary radiation for elements usually found in the gaseous form, and for others difficult to obtain pure, and in this way the list of elements shown on curves D was considerably extended, especially as regards the first period, and the third long period, as mentioned above.

It was pointed out that the atomic weight of an element could be determined with considerable accuracy by measuring the secondary radiation from it, especially if it were situated at a place on the curves where the change of radiation is great as atomic weight changes.

No change of secondary radiation could be detected when the temperature was altered, although observations were made with plates raised to very high temperatures.

In further papers the energy of the secondary radiation was compared with that of the primary  $\beta$ -radiation producing it, and in this connection the relative importance of the secondary  $\beta$ -radiation was emphasised, and it was shown how it must be taken into account in studying the passage of  $\beta$ -particles through matter. This subject was developed theoretically and measurements made which gave the true coefficient of absorption of the  $\beta$ -rays, viz., the value the coefficient would have if no secondary particles were produced. This work showed that the ratio of the true coefficient to the density of the absorbing substance depends on the atomic weight of the substance.

*Subject of Present Paper.*

At the beginning of this work on secondary radiation a few experiments were made on the intensity of the radiation at different inclinations to the normal, and for different angles of incidence, and these few observations indicated that such determinations might give results of importance. They have not, however, been made until now. Comparisons under exactly similar conditions were deemed sufficient for the matters treated in the previous papers, with the exception of the work dealing with the relative energies of the primary and secondary rays, and in that case the conditions were simplified by taking the pencil of primary rays perpendicular to the plate under examination, and measuring for this simple case the intensity of the secondary rays at different inclinations to the normal.

The present paper deals with the intensity of the radiation from the plate in different directions when the incidence rays are not normal. The measurements are carried out with considerable detail in the plane of incidence, and, in addition, measurements are made with another form of apparatus designed to give the total secondary radiation in all directions from the plate for different angles of incidence of the primary rays. One important result of these detailed observations may here be indicated in a few words. A portion of the secondary  $\beta$ -rays follows approximately the ordinary law of reflexion. This portion is not very different in amount, no matter what the plate exposed to the primary radiation consists of. The nature of this portion of the secondary radiation is discussed later; for convenience we shall refer to it in future as the "reflected" portion. When the secondary radiation is measured in such a way as to be comparatively free from reflected rays, it depends on the atomic weight of the substance in an even more striking manner than that shown in the previous work, where the method of measurement was such as to include some reflected rays.

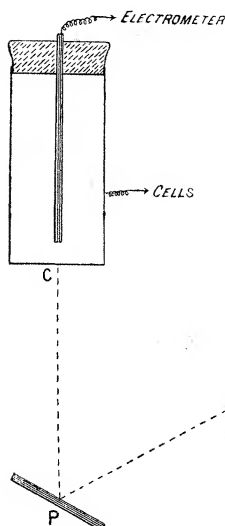
*Apparatus.*

The apparatus used in the first part of the paper was very simple and similar to that employed in the previous experiments.

P represents the material emitting the secondary rays; it is in the form of a circular plate 7.5 cm. diameter, and is exposed to the  $\beta$ -rays from the radium R. P is thick enough to prevent the transmission of  $\beta$ -rays, and thus gives the maximum amount of secondary rays. The radium is enclosed in a short lead tube T which limits, to some extent, the  $\beta$ -rays to a

cylindrical pencil, but the actual intensity of the pencil of rays falling on P, when the angle of incidence is changed, is determined by direct experiment, as described later.

C is a cylindrical vessel 20 cm. long and 7.5 cm. diameter, with a thick wire stretched along its axis and joined to an electrometer, the cylinder



being kept connected to cells and the current to the central terminal measured in the usual way. The end of the cylinder through which the secondary rays enter is covered with a single sheet of tinfoil. The distances CP and RP are each 20 cm.

The tube T and the plate P are both movable, the former around a horizontal circle with P as centre, and the latter about a vertical diameter. When both are turned through the same angle, the angle of incidence remains constant, and measurements of the secondary rays at different angles in the plane of incidence are thus obtained. Such measurements are taken for various angles of incidence.

The plate P can easily be removed and replaced, so that an observation can be taken without the plate, giving the current in C due to unscreened direct radiation from R and other causes, and then another with the plate replaced, the increase being due to the secondary rays from the plate.

In practice it was found inconvenient to screen off the direct rays to a sufficient extent and at the same time retain the necessary freedom of motion of T. The difficulty was met by joining a second ionisation tube like C to the electrometer, and exposing it to a separate small quantity of radium, this second tube being joined to give a charge to the electrometer opposite in sign to that from C. The position of the radium acting on this second tube could easily be adjusted to almost compensate the unscreened radiation from R, and thus enable a sufficiently small capacity to be used with the electrometer.

The amount of primary radiation falling on the plate P is not constant when the angle of incidence  $\theta$  changes, and to reduce the observations to a common basis it is necessary to know the relative amounts for different values of  $\theta$ . This was found by placing the tube T directly facing the cylinder C at a distance from it equal to PR, and measuring the ionisation produced in C when the end facing the radium was covered in succession by a

series of thick lead plates pierced with apertures proportional in area to the different values of  $\cos \theta$ .

It might appear that the comparison thus found would not be accurate, as rays entering through a small area near the centre might not produce the same ionisation as the same rays entering farther from the centre. The error thus introduced was, however, shown to be small, by moving a plate with a small opening in it so as to bring the opening to different positions on the end of the cylinder.

### *Results of Experiments.*

The secondary radiation has been fully studied in the plane of incidence as described above for the elements lead, tin, copper, and aluminium. The primary exciting  $\beta$ -rays are allowed to fall on the exposed plate at a certain angle, and this angle is kept constant, while the intensity of the secondary rays is measured at various angles to the normal, and a curve plotted. The angle of incidence is then altered, and another curve plotted. This has been done for angles of incidence of  $0^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ , and  $75^\circ$ . The curves for the different angles of incidence are then reduced so as to correspond to equal amounts of primary rays impinging on the plate. The numbers required for this reduction are given below, and were determined as has been described.

| Angle of incidence $\theta$ . | Amount of primary rays<br>impinging on plate. |
|-------------------------------|-----------------------------------------------|
| $0^\circ$                     | 100                                           |
| $30^\circ$                    | 96                                            |
| $45^\circ$                    | 79                                            |
| $60^\circ$                    | 62                                            |
| $75^\circ$                    | 34                                            |

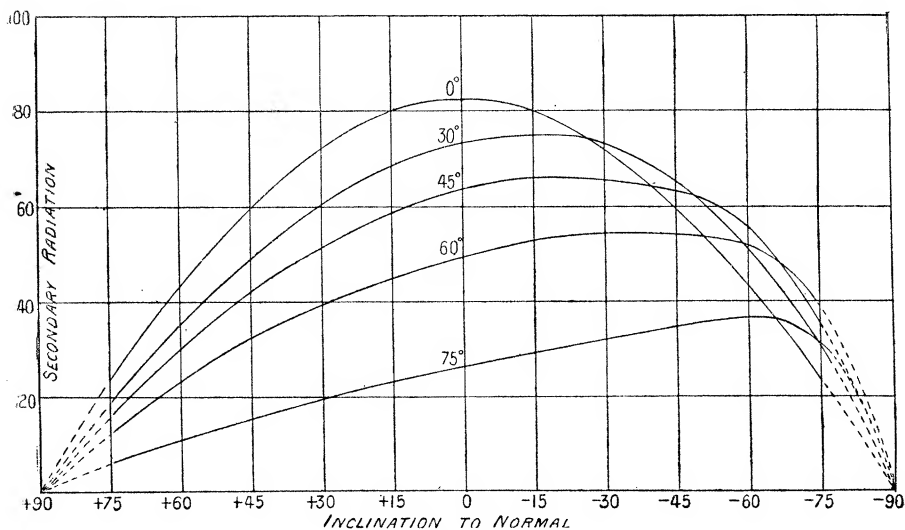
The observations with lead are shown by the curves A. The number on each curve is the angle of incidence of the primary rays, which is constant for all points of the curve. The secondary radiation is plotted for different angles of emission; angles on the same side of the normal as the incident primary rays are marked with a plus sign, and angles on the opposite side with a minus sign. Observations were made at different angles varying from  $+75^\circ$  to  $-75^\circ$ .

Curves B are calculated from Curves A and the numbers given above, so that the curves for different angles of incidence of the primary rays now correspond to equal amounts of primary rays impinging on the plate.

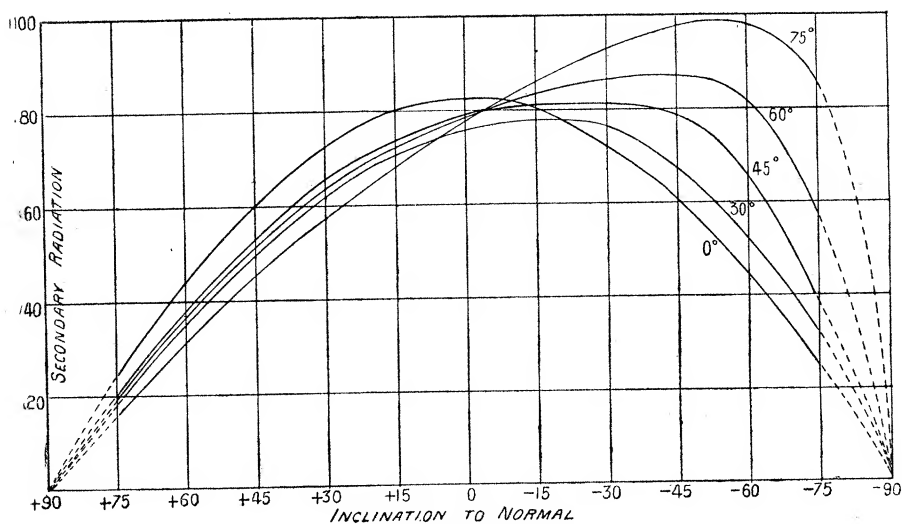
Curves  $A_1$  and  $B_1$  are the similar curves for tin, and curves  $A_2$  and  $B_2$  for

aluminium. The different curves for the same element, and the curves for the various elements, are all plotted to the same scale.

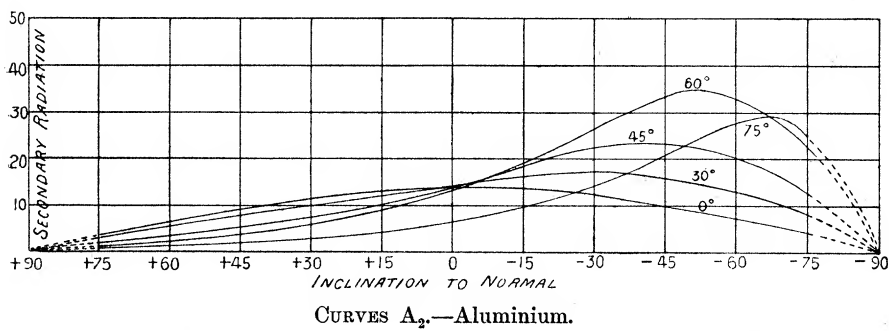
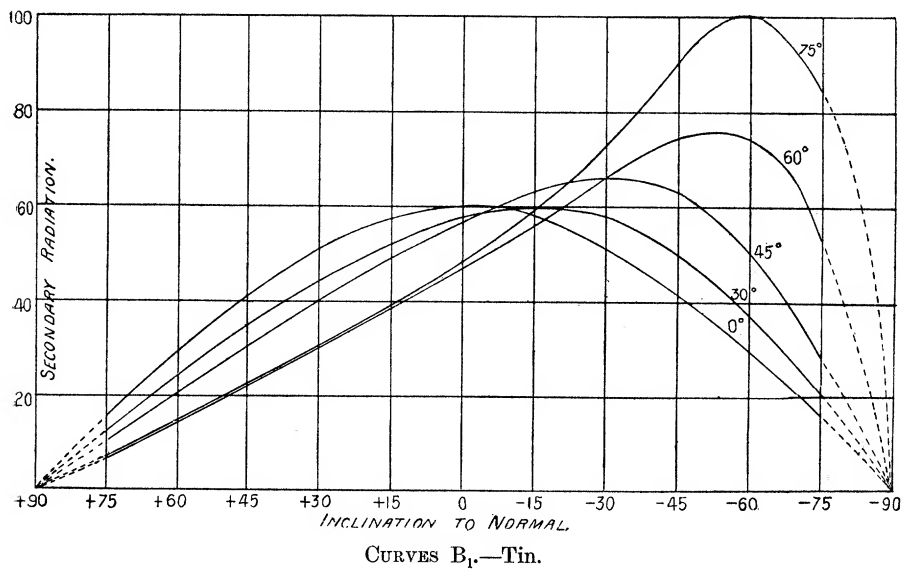
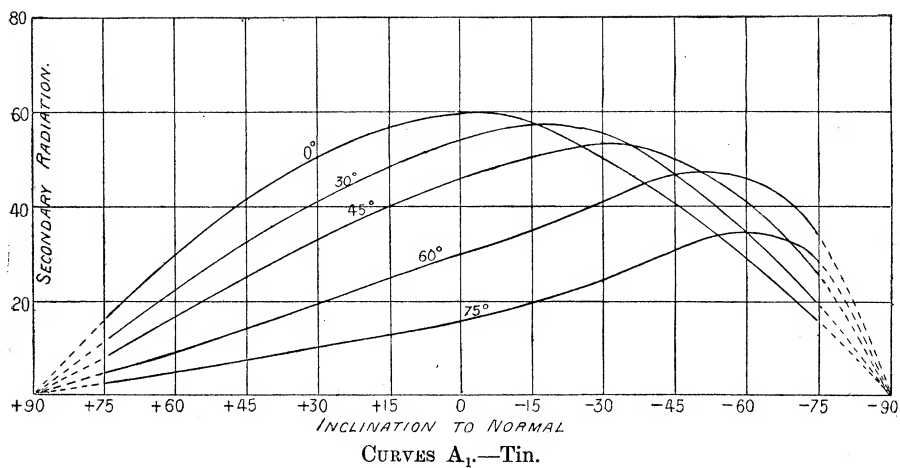
Before describing other experimental results, some of the features of these curves may be briefly referred to. The curve for normal incidence, which is, of course, symmetrical on the plus and minus sides, is almost exactly a cosine curve, showing that when the primary rays are normal to the exposed plate the secondary radiation in any direction is proportional to the cosine of the

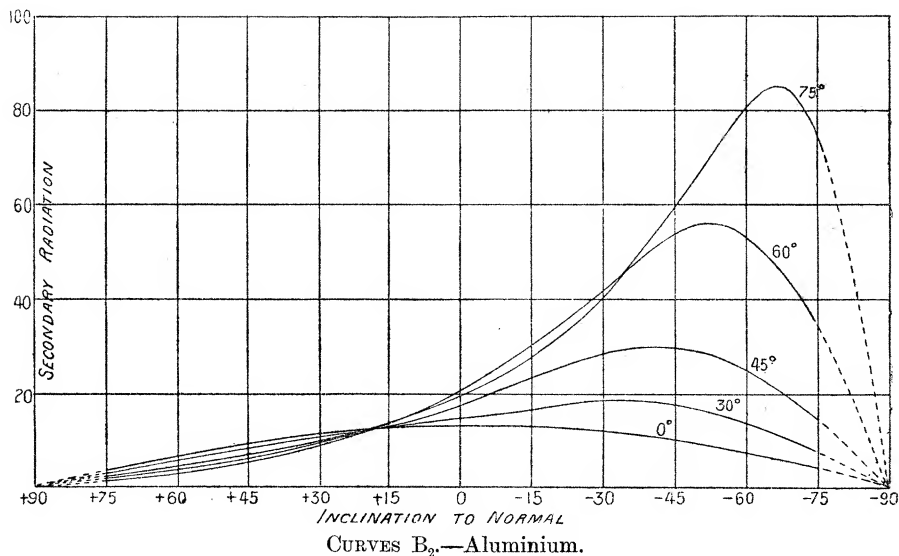


CURVES A.—Lead.



CURVES B.—Lead.





angle between that direction and the normal. This result should follow from the fact that the radiation from an element of volume at a depth in the plate traverses a thickness inversely proportional to the cosine of the angle between its direction and the normal.

The curves for other than normal incidence have a maximum ordinate on the side of the normal away from the direction of the incident rays. The position of the maximum ordinate is more inclined to the normal as the incident rays are more inclined. In fact, the form of the curves suggests that the secondary radiation is made up of two parts, one of which is of importance in directions near to the direction of ordinary reflexion. This reflected portion is evidently a greater fraction of the total secondary in the case of aluminium than in that of tin, and similarly greater for tin than for lead.

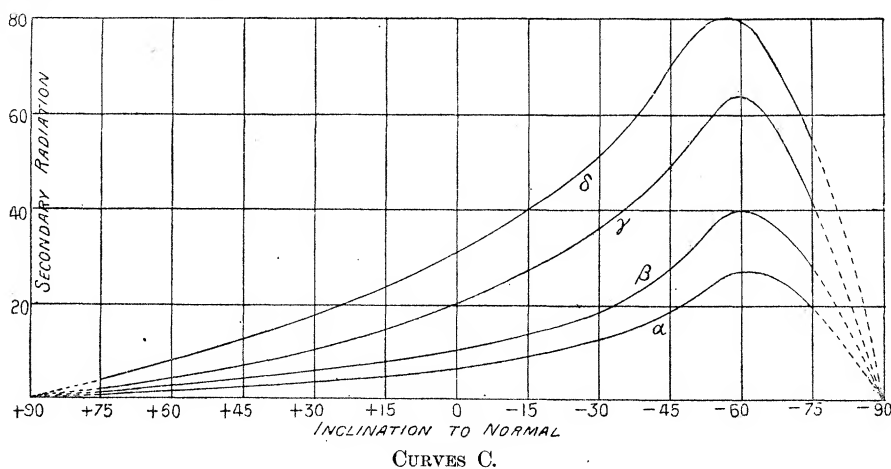
Curves for copper were also plotted, but for economy of space are not reproduced; they were in every sense intermediate in character to those for tin and aluminium. All the results, therefore, agree in showing that the portion of the secondary radiation which we refer to as reflected rays is of greater relative importance the smaller the atomic weight of the substance. This follows, not because the reflected radiation is actually greater for low atomic weights, but because the other portion of the secondary radiation—the true secondary—diminishes rapidly with the atomic weight.

A rough method of analysing the curves is to take the difference between the ordinates for equal angles on the plus and minus sides, and to regard this difference as representing the reflected portion of the secondary radiation. When this is done the position of the maximum of the reflected rays agrees

very closely with the position of ordinary reflexion, and the magnitude of the reflected portion for any angle of incidence does not vary very much for the different elements tested.

*The Effect at the Surface of the Plate.*

To test the effect at the surface of the plate, experiments were carried out with layers of aluminium. Curves C show the results, the separate curves  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$  being for thicknesses of 0.0027 cm., 0.0052 cm., 0.0208 cm., and a large number of layers almost thick enough to give the maximum secondary radiation. The angle of incidence of the primary rays is  $60^\circ$  for each of the



curves, so that the reflected portion is an important part of the whole. The curves are not plotted to scale with those for aluminium given above. An analysis of these curves shows that the reflexion is not merely a surface action, but, as might be expected, it goes on at successive layers beneath the surface. The reflected portion, however, increases less rapidly than the total radiation when the thickness of the plate is increased.

*Absorption of Secondary Rays.*

A few experiments were made on the rate of absorption of the secondary rays: (1) when the primary rays fell normally on the plate and the secondary rays were observed in a direction as near the normal as convenient—about  $15^\circ$  from it; (2) when the angle of incidence was  $60^\circ$ , and the direction of the secondary rays also  $60^\circ$  from normal. In case (1) the radiation should consist almost entirely of true secondary according to the view we have been taking, and in case (2) the reflected portion should be important.

In previous papers the observations required to obtain an accurate value of the coefficient of absorption of rays producing secondary rays were explained; but as for our present purpose we only require approximate relative results, measurements of the ordinary simple type were made. The intensity of the secondary rays was measured before and after passing through an absorbing layer of three sheets of tinfoil. The ratio of the second intensity to the first is given in the following table:—

| Substance emitting the secondary rays. | Ratio of intensities.                                  |                                                                   |
|----------------------------------------|--------------------------------------------------------|-------------------------------------------------------------------|
|                                        | Incident rays normal.<br>Secondary rays 15° to normal. | Incident rays + 60° to normal.<br>Secondary rays - 60° to normal. |
| Pb                                     | 0·63                                                   | 0·74                                                              |
| Pt                                     | 0·63                                                   | 0·74                                                              |
| Sn                                     | 0·60                                                   | —                                                                 |
| Ag                                     | 0·59                                                   | —                                                                 |
| Cu                                     | 0·57                                                   | 0·74                                                              |
| Al                                     | 0·50                                                   | 0·70                                                              |

The corresponding ratio for the primary  $\beta$  radium rays is 0·75.

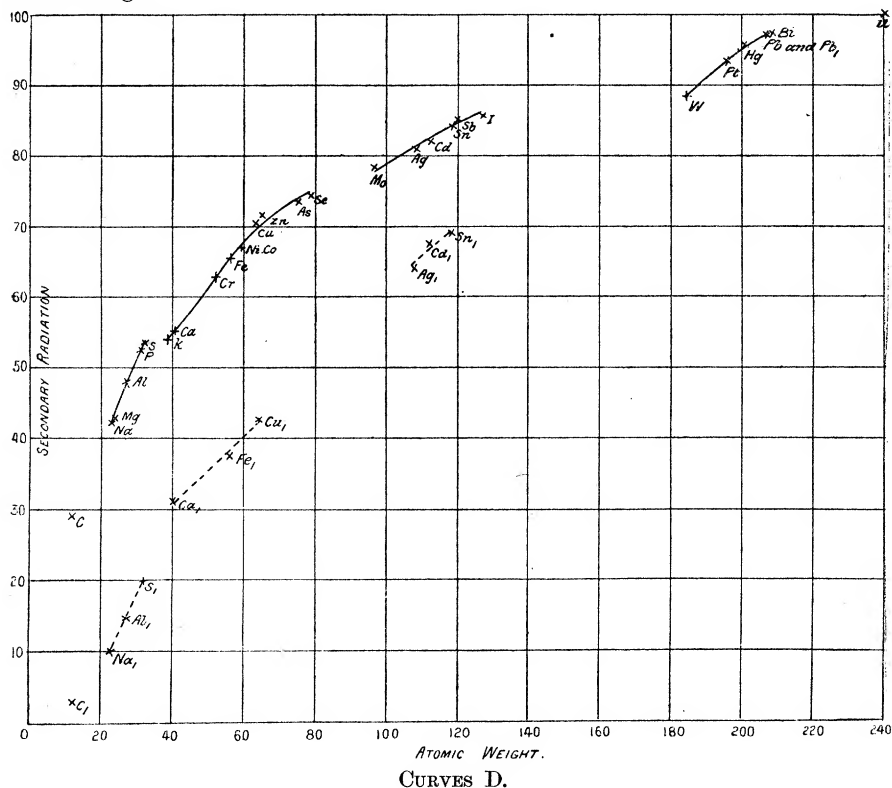
These rough determinations show clearly enough that there is good ground for dividing the total secondary radiation into two distinct parts. When the incident rays are normal, and, therefore, the reflected part small, the rate of absorption of the secondary rays from different substances is decidedly different, and in all cases is greater than that of the primary rays. On the other hand, when the conditions are favourable for greater reflexion, the angles of incidence of primary and emission of secondary being large and equal, the rate of absorption varies much less from one substance to another, and is in all cases not very different from that of the primary rays. A complete investigation of the absorption of the secondary rays from a large number of substances would obviously be of great importance. An interesting connection between the absorption and the atomic weight of the substance emitting the rays would no doubt be found.

#### *Secondary Radiation and Atomic Weight.*

The relation between the intensity of the secondary radiation from an element and its atomic weight has already been described.

The results of previous work are represented by the curves D (continuous part). In these experiments care was taken to place the different elements examined in exactly the same position relative to the incident rays, but this position was such as to give a considerable proportion of what we now call reflected rays. In addition to the experiments with lead, tin, copper, and

aluminium, described above, observations have been made with a few other elements, so as to indicate more fully the new form of these curves connecting secondary radiation and atomic weight when the incident rays fall normally on the exposed plate and the secondary radiation is measured in a direction near the normal;  $15^\circ$  from the normal was taken, as, with the apparatus used, it was inconvenient to make direct measurements for a smaller angle.



The results are shown by the discontinuous curves D, on which the elements are marked with a suffix. The scale used in plotting these curves is such as to make the position of lead coincide with its position on the other curves.

The connection between the secondary radiation and the atomic weight is brought out in an even more striking manner by these later curves, and the divisions corresponding to the chemical periods previously pointed out are quite clear. It would be important to make a fresh examination of a more complete list of elements in the light of the further knowledge regarding the secondary rays that we now possess.

Part II.—MEASUREMENTS OF THE TOTAL SECONDARY RADIATION IN ALL  
DIRECTIONS FOR DIFFERENT ANGLES OF INCIDENCE.

*Apparatus.*

The work described in the first part of this paper is confined to measurements of the secondary radiation in the plane of incidence. To complete the work, similar observations should be carried out in planes other than that of incidence. This has not, however, been done as yet, chiefly on account of the time necessary, but the total secondary radiation has been measured directly.

A form of apparatus was used which gave directly the total radiation in all directions from the exposed plate for different angles of incidence of the primary rays. An ionisation vessel was constructed, consisting of three concentric hemispheres, of radius 20, 25, and 30 cm. respectively, the hemispheres being made of a framework of a few wires, and covered with a single layer of tinfoil. The inner and outer hemispheres rested on a wooden base covered with tinfoil, the two hemispheres and the base being joined to cells and kept at a high potential. The middle hemisphere was insulated from the others and joined to an electrometer, and the ionisation current between the middle and the other hemispheres measured in the usual way. A circular opening at the centre of the base of the hemispheres allowed a plate of the material under examination to be brought into position in the plane of the base from below and removed at will. A narrow opening in the three hemispheres along a meridian allowed a lead tube containing radium to project just inside the inner hemisphere, so that a pencil of  $\beta$ -rays fell on the central portion of the base, including the plate exposed in the circular opening. The difference between the electrometer readings when the plate was in position and when it was removed gave the ionisation due to the secondary radiation from the plate. The tube containing the radium could be moved along the meridian so as to vary the angle of incidence on the exposed plate.

The ionisation vessel, consisting of the space between the middle and the inner and outer hemispheres, being symmetrical with respect to the exposed plate, and thus giving the same path length to all secondary rays, the rates of charging of the inner hemisphere were approximately proportional to the total secondary radiation, irrespective of the distribution of this radiation. Effects due to tertiary and radiations of a higher order might introduce some error, as the symmetry would not hold for such rays.

With this apparatus the conductivity between the hemispheres, due to unscreened direct rays, was necessarily great, but this difficulty was met,

as in the experiments with the former apparatus, by a compensating arrangement. In the present case the current required for approximate compensation was fed into the electrometer by a number of small storage cells acting through a very large variable resistance. Steady results could easily be obtained, as with this apparatus and the quantity of radium used the secondary radiation from plates of 7.5 cm. diameter was large enough to allow the use of a capacity of 0.5 microfarad joined to the electrometer.

*Results of Experiments.*

The total secondary radiation has been measured in this way for lead, tin, copper, and aluminium for angles of incidence of the primary rays ranging from  $10^\circ$  from normal to  $80^\circ$  from normal.

As in the work described in the first part of the paper, the amount of primary radiation impinging on the plate varies with the angle of incidence, and the relative amounts at different angles were determined as before. These relative amounts are given below; they are very similar to the corresponding numbers in the first part of the paper, as the pencils of  $\beta$ -rays used were very similar in the two cases.

| Angle of incidence. | Amount of primary radiation<br>impinging on plate. |
|---------------------|----------------------------------------------------|
| $0^\circ$           | 100                                                |
| $10^\circ$          | 99                                                 |
| $30^\circ$          | 93                                                 |
| $45^\circ$          | 82                                                 |
| $60^\circ$          | 60                                                 |
| $75^\circ$          | 33                                                 |
| $80^\circ$          | 23                                                 |

The total radiations for the four elements tested are given in the following tables. In Table A the observed numbers are given on an

Table A.

| Angle of incidence<br>of primary rays. | Total secondary radiation. |     |     |     |
|----------------------------------------|----------------------------|-----|-----|-----|
|                                        | Pb.                        | Sn. | Cu. | Al. |
| °                                      |                            |     |     |     |
| 10                                     | 58                         | 38  | 24  | 9   |
| 30                                     | 56                         | 37  | 26  | 10  |
| 45                                     | 50                         | 36  | 25  | 12  |
| 60                                     | 41                         | 34  | 25  | 14  |
| 75                                     | 19                         | 15  | 15  | 9   |
| 80                                     | 13                         | 9.5 | 6.5 | 4   |

arbitrary scale, and in Table B these numbers are reduced so as to correspond to equal amounts of primary rays at the various angles, the reduction being made by means of the numbers given above.

Table B.

| Angle of incidence<br>of primary rays. | Total secondary radiation for equal amounts of primary rays. |     |     |     |
|----------------------------------------|--------------------------------------------------------------|-----|-----|-----|
|                                        | Pb.                                                          | Sn. | Cu. | Al. |
| °                                      |                                                              |     |     |     |
| 10                                     | 58                                                           | 38  | 24  | 9   |
| 30                                     | 60                                                           | 40  | 28  | 11  |
| 45                                     | 61                                                           | 44  | 30  | 15  |
| 60                                     | 68                                                           | 57  | 42  | 23  |
| 75                                     | 58                                                           | 46  | 46  | 27  |
| 80                                     | 56                                                           | 41  | 28  | 17  |

A comparison of these numbers, showing the total secondary radiation corresponding to various angles of incidence, with those previously given, showing the secondary radiation in the plane of incidence, enables us to draw some inferences regarding the radiation in planes other than that of incidence. From the way in which the total radiation varies, especially in the case of the elements of lower atomic weight, we see that the "reflected" rays are an important factor of the whole, and are not confined to the plane of incidence. The relative decrease of the total radiation for very large angles of incidence probably means that for such angles the "reflected" radiation is more confined to the plane of incidence than for smaller angles.

#### *Nature of the Secondary $\beta$ -rays.*

The experimental work described in this paper affords strong evidence that the secondary  $\beta$ -rays may usefully be looked upon as consisting of two parts: the true secondary rays, and the "reflected" rays. These two parts differ essentially as regards distribution, they differ somewhat in character, and they probably differ also in origin. The difference in distribution and the variation of the distribution with the angle of incidence of the primary rays have been described at sufficient length, and the difference in character is shown by the measurements on absorption described above.

It is important to consider what difference there may be in the origin of these two parts of the secondary rays.

There is considerable evidence in favour of regarding the reflected rays as consisting of some of the incident  $\beta$ -particles, which, in the path they have

traversed in the exposed plate, have not actually penetrated into or at least not caused any change of energy of any atomic system. Such a particle should leave the plate with its initial velocity unaltered in magnitude. Its velocity parallel to the surface of the plate should also be unaltered, as the resultant forces acting on it should be normal to the plate. Its direction of emergence should therefore be inclined to the normal at an angle equal to that of incidence. These conditions might well be satisfied with sufficient accuracy to explain the observed maximum of reflected rays in the direction corresponding to that of ordinary reflexion.

The other portion of the secondary radiation, called in this paper the true secondary, has been discussed at some length in the previous work referred to at the beginning of this paper. The remarkable relation between the intensity of this radiation and the atomic weight of the substance emitting it was taken as strong evidence that the  $\beta$ -particles composing it were particles expelled from the atoms when disturbed by the entry of the primary rays. If these secondary particles were merely scattered primary particles, it is difficult to see how such a relation between the intensity and the atomic weight could possibly arise. If they are particles expelled from the atom, such a relation would easily admit of explanation.

Whether the expelled particles are original constituents of the atoms, or incident particles absorbed by the atom and subsequently expelled, does not really amount to any essential difference. It is true that from the latter point of view we might, in a sense, regard the secondary particles as scattered primary particles, but scattering in this special sense would, as just stated, be practically identical with the explanation advanced in this and the previous papers.

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